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PACKAGING SYSTEMS INCLUDING RECYCLING

An extended life cycle analysis of packaging systems for fruit and vegetable transport in Europe

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Abstract

Purpose The year-round supply of fresh fruit and vegetables in Europe requires a complex logistics system. In this study, the most common European fruit and vegetable transport packaging systems, namely single-use wooden and cardboard boxes and re-useable plastic crates, are analyzed and compared considering environmental, economic, and social impacts.

Methods The environmental, economic, and social potentials of the three transport packaging systems are examined and compared from a life cycle perspective using Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Life Cycle Working Environment (LCWE) methodologies. Relevant parameters influencing the results are analyzed in different scenarios, and their impacts are quantified. The underlying environmental analysis is an ISO 14040 and 14044 comparative Life Cycle Assessment that was critically reviewed by an independent expert panel.

Results and discussion The results show that wooden boxes and plastic crates perform very similarly in the Global Warming Potential, Acidification Potential, and Photochemical Ozone Creation Potential categories; while plastic crates have a lower impact in the Eutrophication Potential and Abiotic Resource Depletion Potential categories. Cardboard boxes show the highest impacts in all assessed categories. The analysis of the life cycle costs show that the re-usable system is the most cost effective over its entire life cycle. For the production of a single crate, the plastic crates require the most human labor. The share of female employment for the cardboard boxes is the lowest. All three systems require a relatively large share of low-qualified employees. The plastic crate system shows a much lower lethal accident rate. The higher rate for the wooden and cardboard boxes arises mainly from wood logging. In addition, the sustainability consequences due to the influence of packaging in preventing food losses are discussed, and future research combining aspects both from food LCAs and transport packing/packaging LCAs is recommended.

Conclusions For all three systems, optimization potentials regarding their environmental life cycle performance were identified. Wooden boxes (single use) and plastic crates (re-usable) show preferable environmental performance. The calibration of the system parameters, such as end-of-life treatment, showed environmental optimization potentials in all transport packaging systems. The assessment of the economic and the social dimensions in parallel is important in order to avoid trade-offs between the three sustainability dimensions. Merging economic and social aspects into a Life Cycle Assessment is becoming more and more

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important, and their integration into one model ensures a consistent modeling approach for a manageable effort.

Keywords Fruit and vegetables · LCA · LCC · Packaging · Social LCA · Transport

1 Introduction

Every day, thousands of goods make their way from producers to consumers. According to the press release of the *fruit logistica trade fair 2005*, more than 22 million tonnes of fresh fruit and vegetables is traded in Europe every year and is transported in a comparable way to that considered in this study. Transport packaging systems play an essential part in the logistic chain, and wooden boxes, cardboard boxes, and plastic crates are most commonly used for the packaging of fruit or vegetables. According to the vice director of Stiftung Initiative Mehrweg, a German association promoting re-usable packaging, the re-usable transport packaging has an estimated market share of about 40 % in Europe, for single-use packaging cardboard boxes have the largest market shares. Wooden boxes have the lowest market share due to their technical limitations like poor stackability.

Besides bananas, in principle, all kinds of fruit and vegetables are transported in these kinds of transport packaging; thus, the findings of this article are applicable to a huge range of fruit and vegetables. Depending on the size, consistency, humidity, etc. of the fruit and vegetables, specific primary packaging could be necessary for protection and to enable the use of the chosen transport packaging option. The primary packaging is both used in single-use and re-usable packaging, appearing with an enormous diversity. The influence of primary packaging is not covered in this study.

While wooden and cardboard boxes are single-use transport packaging systems and are normally disposed of, incinerated, or partly recycled after single use, plastic crates are generally returnable and are washed and reused multiple times. Wooden and cardboard boxes are based on renewable feedstock while plastic crates use oil-based fossil feedstock. Assessing the sustainability of these widely used transport packaging options in a realistic manner is important to gain knowledge to be able to choose the most preferable packaging option for specific situations.

The sustainability of transport packaging for fruit and vegetables has previously been studied (ADEME 2000; Cagnot et al. 2000; Chonhenchob and Singh 2003; Wagner and Partner SA 2003; RPCC 2004; Capuz et al. 2005; Chonhenchob and Singh 2005; Singh et al. 2006; Barthel et al. 2007; Albrecht et al. 2009; Levi et al. 2011). These studies were generally found to be more specific in scope (with reference to geographical coverage, country-specific recycling options, etc.) than the scope of this current study. Differences in methodology between the existing studies include the choice of goal and scope; the inclusion of different scenarios; the selection of different data sources; the assumptions regarding key parameters (such as the number of circulations of re-usable plastic crates, ranging from 10 to 100); the degree of complexity in modeling the logistics; how open-loop recycling was addressed; the treatment of biogenic CO_2; the extent of the sensitivity analysis, how the interpretation phase of LCA was addressed; who performed the critical review and how it was performed; and, finally, how sustainability was addressed (which pillars of sustainability were taken into account).

The results of the studies also differ; it is well known that system analysis and comparison from a life cycle perspective do not give a unique and static answer. While one study (ADEME 2000) showed that the multiple-use option was environmentally preferable to the cardboard boxes and quite similar to the wooden boxes for most of the environmental impact categories assessed, another study (Capuz et al. 2005) showed the opposite, i.e., that the environmental impact of single-use cardboard boxes was lower than that of re-usable plastic crates in six of the ten categories analyzed.

This paper presents the main results and findings of an extensive LCA study that was first finalized in 2007 and then updated and extended in 2009 (Barthel et al. 2007; Albrecht et al. 2009). This study analyzed and compared the most common transport packaging systems for fruit and vegetables in Europe with respect to the environmental impacts and social and economic aspects related to their use. Given such range of studies that cover the whole life cycle of fruit and vegetable packaging options, including environmental, economic, and social aspects, the study presented here aimed to reproduce an average situation of fruit and vegetable transport for Europe. This average situation is complemented by an extensive parameter analysis. The analysis of the environmental, economic, and social impacts of packaging arguably provides a more objective basis for discussion on sustainable packaging in the fruit and vegetable sector, than the analysis of environmental impacts alone. The results are intended to be used to identify favorable boundary conditions of transport packaging systems for fruit and vegetable distribution throughout Europe (in a representative average situation). The results can be further used for the identification of optimization potentials of a given transport packaging option from a system point of view.

2 The analysis

2.1 Scope of the study

The study analyses and compares transport packaging systems for fruit and vegetable transport in Europe. The

functional unit on which the comparison is based is defined as the distribution of 15 kg of fruits/vegetables in 3,333,350 filled boxes/crates. The fruit/vegetables are transported in either wooden or cardboard boxes, which are both single-use systems, or in re-usable plastic crates. The functional unit reflects the number of boxes/crates necessary to transport 1,000 t of goods five times p.a. accounting for the baseline assumption of five annual circulations per re-usable crate for a time span of 10 years using the most common transport packaging size (600 mm × 400 mm × 240 mm) and comparable capacity (15 kg fruits or vegetables per box). To fulfill the functional unit for the single-use systems, 3,333,350 boxes have to be produced, used, and brought to the end of life. As the plastic crates can be used multiple times, the average lifetime and the number of fillings during the lifetime have to be considered. Primary data give 4.8 fillings per year and an average lifetime of up to 20 years (Albrecht et al. 2009); thus, five fillings per year and a lifetime of 10 years have been chosen as a conservative baseline scenario for comparison. This results in an initial production of 66,667 plastic crates to fulfill the distribution of 3,333,350 filled crates as illustrated in Fig. 1. Prior to washing, the plastic crates are inspected for breakage and replaced if necessary. The average breakage rate during the lifetime of plastic crates is set to 0.47 % as an industry average given by Euro Pool System (2008) and IFCO SYSTEMS (2008), two of the leading logistics service providers of returnable packaging solutions for fresh produce, holding together about 80 % share of the returnable packaging for the fruit and vegetable market in Continental Europe. The damaged crates are identified and removed before cleaning, resulting in around 3.32 million washings and dryings of the plastic crates that are reused. The technical specifications of the systems analyzed are presented in Table 1.

2.2 Product system boundaries

The analysis covers the whole life cycle of the three transport packaging systems, from raw material extraction via production, distribution, and use through to the end of life (recycling and/or disposal or incineration). This includes the extraction of raw materials and fossil fuels, the forestry, the supply of energy and utilities, all transports of primary materials and resources, and the long distance transports of the fruit and vegetable crates and boxes throughout Europe over their lifetime, as shown in Fig. 2.

This study considers fruit and vegetable production and consumption from six countries. Spain, Italy, France, the Netherlands, and Germany represent five of Europe's largest fruit and vegetable producers. France, Germany, the Netherlands, and Great Britain represent a large proportion of Europe's consumed fruit and vegetables. The transportation services are calculated using a transportation matrix, considering the freight transport volume from each producer country to each consumer country combined with the respective transport kilometers driven within the European distribution net. Table 2 provides the determined result of an average European

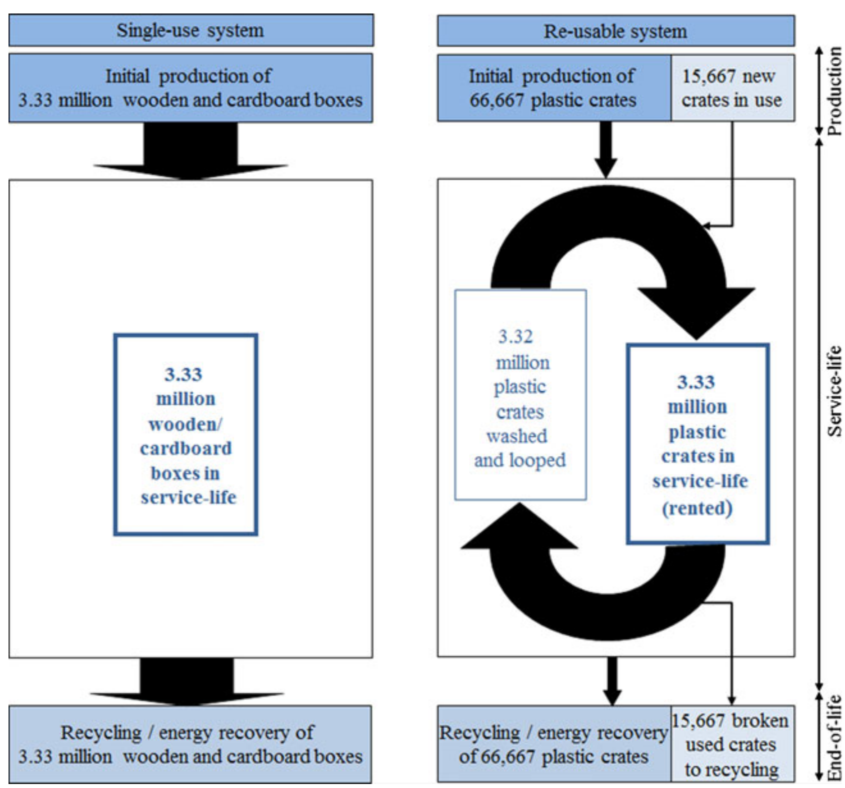

Fig. 1 Overview of the system characteristics over the life cycle of the systems (baseline scenario)

Table 1 Technical specifications of the transport packaging systems analyzed

	Wooden boxes	Cardboard boxes	Plastic crates
Production (material)	Wood	Cardboard	Polypropylene and polyethylene
Service life	Single use	Single use	Re-usable
Re-use	–	–	Cleaning distribution
End of life	Energy recovery Material recycling	Energy recovery Material recycling	Material recycling Energy recovery
Weight per box [kg]	0.9	0.823	2
Dimensions (exterior) [mm]	600×400×240	600×400×240	600×400×240
Load weight (max.) [kg]	15	15	15
Boxes per pallet filled	36	36	36
Layers of boxes per pallet	9	9	9
Pallets per truck (average)	33	33	33
Crates per pallet folded	–	–	213
Crates per truck folded	–	–	7,029
Producer countries (fruit and vegetables)	France, Germany, Italy, Spain, the Netherlands		
Consumer countries (fruit and vegetables)	France, Germany, Great Britain, the Netherlands		

transportation performance [in billion (bn) crates × km and m tonnes × km, resp.] and the mean transportation distance [in kilometer]. The empty re-usable crates have to be additionally transported about 700 km due to the supply to the fruit and vegetable grower. Further system-specific transports occur within the three transport packaging systems, like the transport of new boxes and crates to the growing area or used re-usable crates going into the washing and cleaning centers.

The end-of-life considerations take into account the different opportunities of the specific waste treatment of the three transport packaging systems. The end-of-life options for single-use wooden boxes are incineration with energy recovery and recycling into particleboard. As through composting no high-value industrial products are gained, composting is neglected in this study. The baseline assumptions are a 100 % incineration with respective electricity grid mix credits. No credit was given to steam, as steam from waste incineration is not saleable in some regions in Europe.

To fulfill the high requirements of fruit and vegetable transport, the production of the single-use cardboard boxes

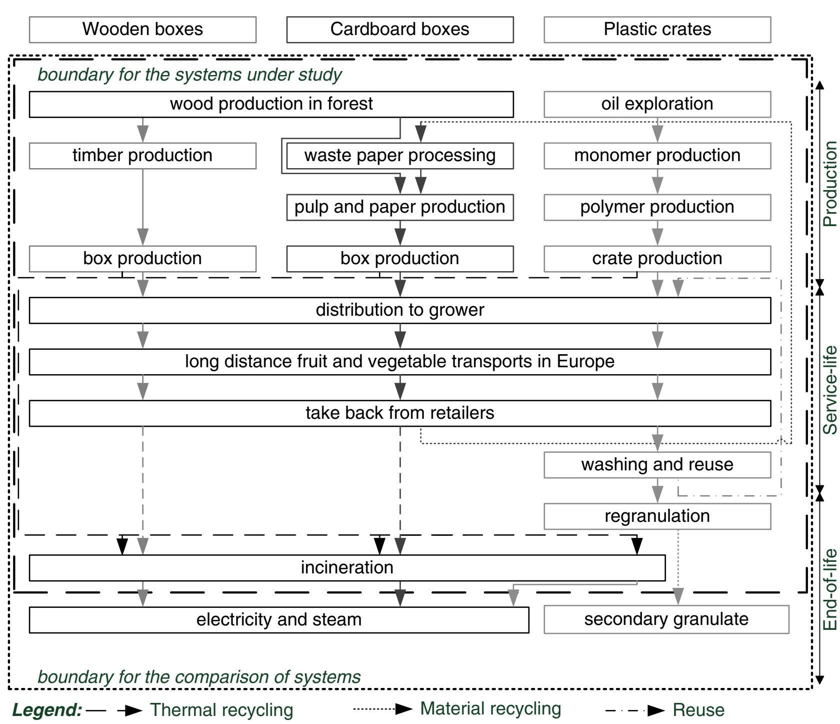

Fig. 2 System boundary overview

Table 2 Transportation performance and respective mean transportation distance

Average European transport performance and distance	Calculated average Full boxes and crates
Transportation performance [bn crates × km]	3.34
Transportation performance [m tonnes × km]	50
Mean transportation distance [km]	1,003

requires a high-quality paper with 82.4 % primary source material, the rest being recycled material (FEFCO 2006). Hence, in the baseline scenario, it is assumed 17.6 % of the cardboard boxes are looped back into pulp and paper production after use to meet the needed input on recycled material. The rest of the cardboard is considered to be incinerated in the waste incineration with energy recovery.

In the case of the re-usable plastic crates, the material is assumed to be recycled. As the plastic crates stay in the possession of the logistics service provider, at the end of life, the respective secondary granulates are identical to the chemical composition, additives content, color, etc. of the primary material. Thus, a high-level recycling within the same or similar application is a standard procedure. The secondary granulate is mainly used to produce new plastic crates, either for re-usable plastic crates for fruit and vegetable transport or for other applications like beer or water crates. Therefore, in the baseline scenario, an open-loop recycling is assumed, and the value of the secondary granulate is set to 70 % of the virgin material with respect to some potential degradation of the recycled material.

The carbon incorporated during the growth of wood is considered as a net Global Warming Potential (GWP) intake in the production phase. Combined with the CO_2 emissions from the end-of-life phase, the balance for biogenic carbon is closed.

2.3 Data

Primary data (Albrecht et al. 2009) were primarily gathered from industry, relevant associations, and published literature. All relevant background data such as energy, transport, and auxiliary materials were taken from the database of the software system GaBi 4. The majority of the datasets used are publicly available, and public documentation exists (GaBi 2008a). The rationale behind, the main structure of the models, etc. was already determined in Barthel et al. (2007); in 2009, an update of this study was released (Albrecht et al. 2009). The main changes affecting this article are an upgrade of all GaBi LCI background datasets. Further foreground data have been updated, as the use of the updated upstream chain data of the cardboard boxes (FEFCO 2006). Data on the service life of plastic crates have been updated, mainly new energy and water consumption data as well as emission data from the washing processes and updated breakage rates (IFCO 2008; EURO POOL SYSTEM 2008). Further, some data on wooden box production have been adopted according to GROW (2008).

2.4 Methods applied

In this study, environmental, economic, and social aspects are considered, giving an approach to an overall sustainability assessment in its broader sense. Environmental effects are evaluated using the Life Cycle Assessment method according to the ISO standards ISO 14040 (ISO 2006) and ISO 14044 (ISO 2006). The following environmental indicators and impact categories using Centrum voor Milieukunde Leiden (CML) indicators (Guinée et al. 2002) are assessed:

- The Primary Energy Demand (PED)—demand of fossil and renewable energetic resources
- The GWP—“anthropogenic greenhouse effect”
- The Acidification Potential (AP)—contribution to “acid rain”
- The Eutrophication Potential (EP)—contribution to “over fertilization”
- The Photochemical Ozone Creation Potential (POCP)—contribution to “summer smog”
- The Abiotic Resource Depletion Potential (ADP)—depletion of non-renewable non-organic materials

The traditional *one-point study*, which considers a fixed set of boundary conditions and situations, is not performed here. Instead, a representative baseline scenario is chosen and assessed. The relevant parameters influencing the life cycle are then identified and varied, and the resulting changes in the environmental impacts are discussed.

Economic aspects are considered by performing a Life Cycle Costing (LCC) analysis within the same system boundaries as the environmental baseline scenario. The basis for the comparison is the same life cycle model underlying the LCA study. All relevant cost units for production, transportation, and distribution of the empty boxes/crates, applicable cleaning and washing, costs/revenues for the end of life of the different materials, etc. are considered.

The Life Cycle Working Environment (LCWE) method (Barthel et al. 2005, 2007; Makishi Colodel et al. 2009), also described as WE-LCA (Benoît et al. 2009), is applied for the production and the service life in order to cover the social aspects of the systems. This method employs social indicators for each process in the process chain. The applied indicators are at an inventory level; the establishment of an impact assessment for social indicators continues. These indicators are summed up over the whole process chain to

account for all social effects caused by the product. The unit "seconds of work" is used as a weighting factor for the different processes. The indicators used for the study are:

- The total time of work [second/package]
- The total time of women's work [second/package]
- The differentiation of the working time into qualification levels [second/package]
- The number of lethal and non-lethal accidents [cases/package].

The indicator data used are provided at the industry level by national databases and are broken down to processes using "value added" as an allocation key (Barthel et al. 2005, 2007).

2.5 Critical review

LCA studies that include a publically disclosed comparative assertion affect the interests of competitors and other stakeholders, especially when the results are controversial or show high economic implications such as in the logistics market. The overarching aim of any critical review is to contribute to the quality assurance of LCA studies and to protect interested parties on the marketplace from unsubstantiated claims.

The main results presented were derived from an extensive study completed in 2007, which was then updated and extended in 2009 (Barthel et al. 2007; Albrecht et al. 2009). The environmental impact assessment is a comparative Life Cycle Assessment according to ISO standards 14040 (ISO 2006) and 14044 (ISO 2006), and the findings are intended to be disclosed to the public. Therefore, in line with these standards, the LCA components of the underlying studies were critically reviewed by international external review panels.

The critical review process ascertained the transparent documentation of the purpose and use of the studies as well as the consistent life cycle models and the data categories. Accordingly, the data, models, and methods employed are deemed appropriate, in relation to the goal and scope of the study.

3 Results and discussion

3.1 Life cycle indicator results

PED is used as a measure of the cumulative primary energy resources that are used directly and indirectly over the life cycle of the system. The calculated results for the PED are shown in Table 3. The total PED results are split into primary energy expenditure (*PED total consumption (production + service life)*) and end-of-life credits (*PED total substitution (end of life)*). The PED total consumption (*production + service life*) is a sum of *PED non-renewable consumption* and *PED renewable consumption*, and primarily reflects the consumption of primary energy resources for both the production of the materials used and for the energy needed to run the service-life processes. PED total substitution (end of life) is a sum of PED substitution non-renewable and PED substitution renewable, and accounts for credits from the end-of-life treatment—for example from energy recovery. The non-renewable component of the primary energy consumption is by definition a depletion (of fossil energy resources), whereas the renewable component is not depleted in this sense.

The cardboard boxes and the plastic crates show almost the same level of PED non-renewable consumption. The wooden boxes and the cardboard boxes have a high consumption in terms of primary energy from renewable resources (PED renewable consumption). The use of non-renewable resources is avoided as a result of the energy produced from incineration and energy recovery of the wooden and cardboard boxes after use. This results in a reduction in the PED non-renewable total for the cardboard boxes. The wooden boxes generate more non-renewable primary energy (PED substitution non-renewable) at end of life than is necessary for their production, resulting in a net negative contribution.

The PED of wooden boxes is mainly based on solar energy captured via photosynthesis. The wooden box system recovers the highest amount of the used embodied energy and therefore substitutes more non-renewable primary energy than what is used.

The cardboard boxes have the highest PED total. The relation of PED non-renewable total to PED renewable total for the cardboard boxes is one to four. The cardboard system recovers about one third of the total primary energy.

The plastic crates show almost the same level of PED non-renewable total, but due to a lower amount of PED renewable total, the overall PED total is lower than both single-use systems.

When analyzing and discussing the depletion of energy resources from a present view, the PED non-renewable can be seen to be the more important indicator. From a life cycle perspective and from the calculation of end-of-life credits with respect to a potential substitution of non-renewable resources by renewables, the information gained by PED renewable deepens the outcomes from the analysis of non-renewable resource depletion. The PED indicators include the particular embodied energy. This is caused by two related aspects. At first, savings in the consumption of PED non-renewable in production are caused by the use of renewable waste products as an energy source in production and due the renewable embodied energy with the wooden and cardboard boxes. These savings mainly result from the less energy intensive wooden boxes and to a minor extent from cardboard boxes due to a more complex and energy demanding processing. Secondly, at the end of life, this renewable embodied energy gains credits in PED non-renewable when, for example, wooden boxes are incinerated

Table 3 PED of the baseline scenario

Life cycle PED [MJ per functional unit]	Wooden boxes (single use)	Cardboard boxes (single use)	Plastic crates (re-usable)
PED non-renewable consumption	19,050,000	49,150,000	19,670,000
PED renewable consumption	77,980,000	77,590,000	310,000
PED total consumption (production + service life)	97,030,000	126,740,000	19,980,000
PED substitution non-renewable	−37,030,000	−31,280,000	−3,240,000
PED substitution renewable	−16,380,000	−6,000,000	−60,000
PED total substitution (end of life)	−53,410,000	−37,280,000	−3,300,000
PED non-renewable total	−17,980,000	17,870,000	16,430,000
PED renewable total	61,600,000	71,590,000	250,000
PED total	43,610,000	89,460,000	16,680,000

in a Municipal Solid Waste Incinerator (MSWI) and substituting potentially fossil-based power grid mixes. The depletion of non-renewable energy carriers is further addressed by the calculation of ADP (see Section 3.2).

3.2 Life cycle impact assessment results

A representative baseline scenario with the corresponding parameter settings (*baseline scenario (representative mean value)*) was calculated, in order to estimate the influence of technical and organizational parameters on the system. These parameters included aspects such as lifetime, efficiencies, and the number of fillings; see Table 4. The results of these calculations reflect an average situation for each transport packaging system in a European-wide context. The results have to be interpreted carefully, knowing that a model is a mirror of a variable reality. A single truth rarely exists in reality, and this should be reflected by LCA as well.

The results are first presented as a range relative to the baseline scenario. The results of the environmental impact categories are shown in Table 4 as absolute values and in Fig. 3 as normalized to the annual European emissions according to Guinée et al. (2002), which were updated in 2007.

The overall results for five environmental impacts are presented below. Table 4 provides the absolute results for the baseline scenario split into three parts: emitted, avoided, or incorporated, and total impacts.

The figures under *emitted* correspond to the total releases over the life cycle; the figures for *avoided* or *incorporated* reflect the effects due to incorporation of CO_2 during the growth of renewable resources and the effects of avoiding or substituting primary production through the use of used by-products, energy, and secondary materials. The *total impact* figures represent the balance of both (emitted minus avoided/incorporated).

The trees from which the wooden boxes are made incorporate carbon dioxide during growth. This carbon dioxide is released when the boxes are incinerated. Electricity is produced during incineration and substitutes/avoids average electricity production. Cardboard boxes emit more CO_2 during production than wooden boxes and have less CO_2 incorporation as only a portion of the input materials and chemicals are wood based. The combined effects of the larger number of boxes produced and *the smaller quantity of incorporated CO_2* result in higher net CO_2 emissions, despite the fact that the cardboard boxes are by far the lightest boxes and therefore emit less CO_2 during road transport than wooden boxes and plastic crates. Eighty-two percent of the cardboard boxes are incinerated, and the incorporated CO_2 is released. The remaining 18 % are used to satisfy a secondary pulp demand in the production of the fruit and vegetable boxes. Plastic crates emit significantly less carbon dioxide in the production phase than the other options due to the characteristics of a re-usable system, where fewer crates need to be produced. However, plastic crates do not benefit from uptake of carbon dioxide prior to production. The end of life of the plastic crates show a benefit over the life cycle, due to the recycling of the crates with substitution of primary material and the incineration and energy recovery of production residues.

Under the given boundaries, the eutrophication impact, caused by emissions to water and air, is lowest for the plastic crate system, followed by wood and cardboard. For cardboard, this is mainly due to the production of *Kraftliner* and *Fluting* (86 % of total over the life cycle). The cardboard for fruit and vegetable boxes completely consists of the high-quality pulp systems Kraftliner and Semi-Chemical Fluting (FEFCO 2006) as these systems are suitable for a humid atmosphere. The EP impacts of the wooden boxes are mainly due to the box production stage and to the distribution of new boxes to growers (both approx. 25 %); approx. 20 % of the impact is from the supply of wood, 15 % is due to the service life stage and transports, and 15 % due to the end-of-life stage. The EP of the plastic crates is driven by their service life. About 70 % of the emissions are caused by transports. The washing and the production of the crates also contribute significantly to this impact, with about 25 % of emissions coming from these sources.

Table 4 Life cycle impacts per functional unit (baseline scenario) divided into most important life cycle steps

	Life cycle impacts per functional unit (FU)		Production			Service life		End of life			
Single-use wooden boxes	Emitted	Wooden boxes	Forestry + timber prod.	Prod. of boxes	Distribution to grower	Delivery and take-back	Long-distance transport	Transports incinerat.	Incineration	Energy recovery	
	GWP [kg CO_2-Eq./FU]	9,740,000	320,000	3,200,000	370,000	90,000	150,000	10,000	5,600,000	–	
	AP [kg SO_2-Eq./FU]	10,200	2,000	3,100	2,200	580	880	40	1,400	–	
	EP [kg PO_4^{3-}-Eq./FU]	1,670	300	400	400	100	160	10	300	–	
	POCP [kg C_2H_4-Eq./FU]	1,660	400	370	460	120	180	10	120	–	
	ADP [kg Sb-Eq./FU]	1,000	–	–	–	–	–	–	–	1,000	
	Avoided or incorporated										
	GWP [kg CO_2-Eq./FU]	8,500,000	8,000,000	300,000	–	–	–	–	–	200,000	
	AP [kg SO_2-Eq./FU]	1,600	–	–	–	–	–	–	–	1,600	
	EP [kg PO_4^{3-}-Eq./FU]	100	–	0	–	–	–	–	–	100	
	POCP [kg C_2H_4-Eq./FU]	100	–	–	–	–	–	–	–	100	
	ADP [kg Sb-Eq./FU]	9,750	2,000	2,500	2,500	600	1,000	50	1,100	–	
	Total										
	GWP [kg CO_2-Eq./FU]	1,240,000	−7,680,000	2,900,000	370,000	90,000	150,000	10,000	5,600,000	−200,000	
	AP [kg SO_2-Eq./FU]	8,600	2,000	3,100	2,200	580	880	40	1,400	−1,600	
	EP [kg PO_4^{3-}-Eq./FU]	1,570	300	400	400	100	160	10	300	−100	
	POCP [kg C_2H_4-Eq./FU]	1,560	400	370	460	120	180	10	120	−100	
	ADP [kg Sb-Eq./FU]	8,750	2,000	2,500	2,500	600	1,000	50	1,100	−1,000	
Single-use cardboard boxes			Production			Service life		End of life			
	EMITTED	Cardboard boxes	Forestry + wood prod.	Pulp and paper prod.	Cardboard prod. + distrib. to grower	Delivery and take back	Long distance transport	Transports + Mill	Incineration	Energy recovery	Recovered pulp
	GWP [kg CO_2-Eq./FU]	10,820,000	48,000	6,100,000	580,000	86,000	140,000	12,000	3,800,000	–	54,000
	AP [kg SO_2-Eq./FU]	22,550	400	18,200	2,200	500	800	150	300	–	–
	EP [kg PO_4^{3-}-Eq./FU]	4,570	60	3,900	270	100	140	20	80	–	–
	POCP [kg C_2H_4-Eq./FU]	2,390	220	1,600	230	110	160	20	50	–	–
	ADP [kg Sb-Eq./FU]	3,500	–	1,300	–	–	–	–	–	200	2,000
	Avoided or incorporated										
	GWP [kg CO_2-Eq./FU]	8,460,000	7,000,000	860,000	300,000	–	–	–	–	30,000	270,000
	AP [kg SO_2-Eq./FU]	1,400	–	400	–	–	–	–	–	300	700
	EP [kg PO_4^{3-}-Eq./FU]	190	–	50	0	–	–	–	–	10	130
	POCP [kg C_2H_4-Eq./FU]	170	–	80	–	–	–	–	–	20	70
	ADP [kg Sb-Eq./FU]	21,520	200	15,000	3,800	600	1,000	120	800	–	–
	Total										
	GWP [kg CO_2-Eq./FU]	2,360,000	−6,952,000	5,240,000	280,000	86,000	140,000	12,000	3,800,000	−30,000	−216,000
	AP [kg SO_2-Eq./FU]	21,150	400	17,800	2,200	500	800	150	300	−300	−700
	EP [kg PO_4^{3-}-Eq./FU]	4,380	60	3,850	270	100	140	20	80	−10	−130
	POCP [kg C_2H_4-Eq./FU]	2,220	220	1,520	230	110	160	20	50	−20	−70
	ADP [kg Sb-Eq./FU]	18,020	200	13,700	3,800	600	1,000	120	800	−200	−2,000

Table 4 (continued)

Re-usable plastic crates			Production			Service life				End of life			
	EMITTED	Plastic crates	Prod. plastic granulate	Prod. of crates	Distribution to grower	Delivery and take-back	Long distance transport	Backhaul	Inspection and washing	Transports + Mill + Regranul.	Incineration of residues	Energy recovery	Recovered granulate
	GWP [kg CO_2-Eq./FU]	1,426,000	300,000	30,000	70,000	210,000	450,000	67,000	290,000	6,000	3,000	–	–
	AP [kg SO_2-Eq./FU]	6,442	740	190	40	1,300	2,000	360	1,550	260	2	–	–
	EP [kg PO_4^{3-}-Eq./FU]	911	90	10	10	230	360	70	130	10	1	–	–
	POCP [kg C_2H_4-Eq./FU]	1,591	600	30	10	270	460	20	180	20	1	–	–
	ADP [kg Sb-Eq./FU]	3,780	–	–	–	–	–	–	–	–	–	12	3,768
	Avoided or incorporated												
	GWP [kg CO_2-Eq./FU]	197,760	0	350	–	–	–	–	10	–	–	2,400	195,000
	AP [kg SO_2-Eq./FU]	540	–	–	–	–	–	–	–	–	–	20	520
	EP [kg PO_4^{3-}-Eq./FU]	61	–	–	–	–	–	–	0	–	–	1	60
	POCP [kg C_2H_4-Eq./FU]	501	–	–	–	–	–	–	–	–	–	1	500
	ADP [kg Sb-Eq./FU]	12,190	5,600	170	50	1,400	2,800	–	2,000	160	10	–	–
	Total												
	GWP [kg CO_2-Eq./FU]	1,228,240	300,000	29,650	70,000	210,000	450,000	67,000	289,990	6,000	3,000	−2,400	−195,000
	AP [kg SO_2-Eq./FU]	5,902	740	190	40	1,300	2,000	360	1,550	260	2	−20	−520
	EP [kg PO_4^{3-}-Eq./FU]	850	90	10	10	230	360	70	130	10	1	−1	−60
	POCP [kg C_2H_4-Eq./FU]	1,089	600	30	10	270	460	20	180	20	1	−1	−500
	ADP [kg Sb-Eq./FU]	8,410	5,600	170	50	1,400	2,800	–	2,000	160	10	−12	−3,768

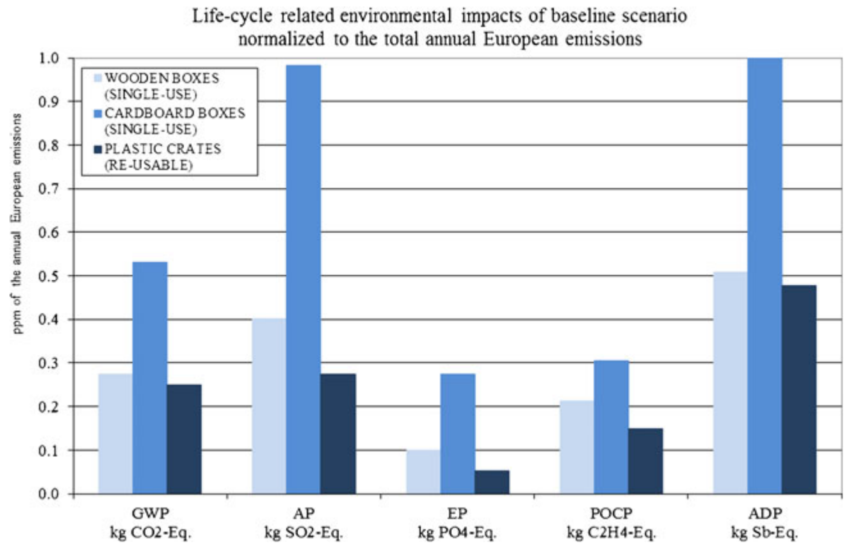

Fig. 3 Environmental impacts of the baseline scenario normalized to the total annual European emissions using CML indicators (Guinée et al. 2002)

The analysis of the results for EP is valid for AP as well. The same contributors play the most important roles and the results are similar. For the POCP impact, the largest impacts arise from the supply of the energy carriers electricity and fossil-based fuels. The use of energy therefore has a major influence on the POCP impact. The ADP impacts follow the consumption of non-renewable primary energy as shown in Table 3, which corroborates the overall findings of the environmental impact assessment. Overall, the advantage of the re-usable crate system lies in the ability of the crates to be reused, which therefore reduces the need for plastic crate production.

The "avoided impacts" of all three systems reflect the positive effects of recovering energy in thermal treatment units such as incineration plants and of recovering secondary materials in recycling. The electricity is sold and substitutes average electricity production in the EU25, while the secondary materials substitute a part of primary material production.

The absolute results shown in Fig. 3 are related to Europe's total emissions for the relevant impact category in the year 2007 (Guinée et al. 2002). The main contributors to these impacts are discussed above. The contribution of the transport packaging systems to the annual European total is most significant in AP, ADP, and GWP, followed by POCP and EP.

Table 5 gives an overview of the main parameter settings for the baseline scenario, which were chosen as a reference for the discussion of results. Alternative parameter values and the resulting life cycle impacts are shown relative to the baseline scenario.

The parameters in Table 5 are shown per life cycle phase, as well as by the respective transport packaging system. The results in the section *Changes in environmental impacts relative to the baseline scenario* are to be understood as follows: negative relative numbers improve the Life Cycle Impact Assessment (LCIA) results while positive numbers represent a deterioration of the environmental profiles.

The different parameters are numbered (no. 1–23). A variation in the value of these parameters is shown within a meaningful range. Some of the parameter variations can be seen as a sensitivity analysis showing the extent to which the system is sensitive to variability (no. 7–12). In these cases, a minor sensitivity outcome attests to the stability of the system and shows that possible uncertainties in these values do not have a notable influence on the results. The remaining parameters (no. 1–6 and 13–23) should be interpreted as a parameter variation showing the results of different assumptions in order to highlight key drivers and optimization potentials. The parameters that result in large changes to the overall results are discussed below.

Production The production of the wooden boxes is mainly influenced by the share of ligneous crops, the presence or absence of technical wood drying, and the application of steaming prior to peeling of poplar wood (no. 1–4). Only the application of steaming of poplar prior to peeling (no steaming is assumed in the baseline scenario) shows significant environmental relevance; it worsens the environmental profile of the production of wooden boxes by up to 12 % in GWP due to the additional thermal energy required for biomass heating.

The parameter with the highest impact within the production phase of the cardboard boxes is the specific share of different pulps and papers (no. 5). According to FEFCO (2006), the composition of fruit and vegetable boxes is characterized by high shares of Fluting and Kraftliner, which are two high-quality, demanding paper types, which are able to withstand the humid atmosphere present during the transport of fruit and vegetables. The variation of this parameter is therefore not a technical option for the defined functional unit, as this specific paper quality is required. Nevertheless, a variation indicates the importance of this parameter and its relevance. The variation in the factors

Table 5 Parameter settings and subsequent variation in the life cycle impact assessment results

No.	Main production parameters	Baseline scenario (representative mean value)	Varied to value	Changes in environmental impacts relative to the baseline scenario					
				GWP	AP	EP	POCP	ADP	Remarks
Wooden box production									
1	Share of poplar in box production	80 %	0 %	7.9 %	4.4 %	1.3 %	5.1 %	3.3 %	Only poplar or no poplar used for wooden boxes
	Share of pine in box production	11.3 %	57 %						
2	Share of spruce in box production	8.7 %	44 %	−2.0 %	−1.1 %	−0.3 %	−1.3 %	−0.8 %	
	Share of poplar in box production	80 %	100 %						
	Share of pine in box production	11.3 %	0 %						
	Share of spruce in box production	8.7 %	0 %						
3	Share of wood dried during box production	20 %	50 %	2.3 %	0.9 %	0.2 %	0.3 %	0.6 %	20 % drying reported. 50 % assumed as higher value for regions with higher humidity or lower temperatures
4	Share of poplar wood steamed prior to peeling	0 %	100 %	11.9 %	9.6 %	5.0 %	5.2 %	0.0 %	Check of influence of steaming
Cardboard box production									
5	Share of Semi-Chemical Fluting in cardboard box	63 %	10 %	18.4 %	−49.1 %	−50.5 %	−45.0 %	−3.1 %	Average cardboard boxes assumed (not suitable for fruit and vegetable boxes due to humidity and rigidity requirements, just for verification purposes)
	Share of Kraftliner in cardboard box	37 %	21 %						
	Share of Testliner in cardboard box	0 %	33 %						
	Share of Wellenstoff in cardboard box	0 %	33 %						
Plastic crate production									
6	Share of primary plastic material in production of crates	100 %	70 %	−2.9 %	−1.1 %	−1.0 %	−2.5 %	−6.4 %	30 % secondary granulate considered as realistic for possible secondary granulate use (even more possible)
7	Share of primary polyethylene material in production of crates	58 %	100 %	0.4 %	0.3 %	0.4 %	−2.6 %	−0.1 %	
8	Share of primary polypropylene material in production of crates	42 %	100 %	−0.3 %	−0.2 %	−0.3 %	1.9 %	0.2 %	Only PP crates used or only PE crates used respectively
9	Granulate losses during production of crates	2.75 %	1.50 %	−0.1 %	−0.1 %	0.0 %	−0.1 %	−0.1 %	Range of collected data
10	Granulate losses during production of crates	2.75 %	6 %	0.2 %	0.3 %	0.1 %	0.3 %	0.3 %	Range of collected data
11	Damaged crates prior to washing in relation to total crates inspected	0.47 %	0.17 %	−2.2 %	−1.4 %	−0.8 %	−1.7 %	−8.8 %	Range of collected data
12	Damaged crates prior to washing in relation to total crates inspected	0.47 %	0.71 %	1.7 %	1.1 %	0.6 %	1.3 %	2.5 %	Range of collected data
No.	Main service-life parameters	Representative mean value (benchmark basis)	Varied to value	Changes in environmental impacts relative to the baseline scenario					
				GWP	AP	EP	POCP	ADP	Remarks

Table 5 (continued)

No.	Main production parameters	Baseline scenario (representative mean value)	Varied to value	Changes in environmental impacts relative to the baseline scenario: GWP	AP	EP	POCP	ADP	Remarks
Plastic crates service life									
13	Lifetime Rotations	10 years 5 per year	20 years	−7.3 %	−4.7 %	−2.6 %	−5.7 %	−10.4 %	This represents an average technical lifetime of the plastic crates assuming 5 rotations per year
14	Lifetime Rotations	10 years 5 per year	6 years	9.8 %	6.3 %	3.5 %	7.6 %	13.9 %	This represents a low lifetime of the plastic crates assuming 5 rotations per year not fulfilling the technical possibilities
No.	Main end-of-life parameters	Representative mean value (benchmark basis)	Varied to value	Changes in environmental impacts relative to the baseline scenario: GWP	AP	EP	POCP	ADP	Remarks
Wooden boxes end of life									
15	Share of wood to incineration (rest to particle board industry) Products from incineration of wood	100 % Electricity	0 %	29.3 %	19.8 %	2.1 %	17.6 %	17.3 %	No incineration of wooden boxes or 50 % incineration of wood crates considered
16	Share of wood to incineration (rest to particle board industry) Products from incineration of wood	100 % Electricity	50 %	10.2 %	9.9 %	−3.0 %	8.8 %	8.6 %	
17	Sold steam products from incineration in MSWI	0 %	100 %	−104.5 %	−20.9 %	−12.0 %	−16.3 %	−120.2 %	Steam from waste incinerators is not saleable in some regions
Cardboard boxes end of life									
18	Value of fibers in relation to Wellenstoff	90 %							
19	Fiber allocation according to ISO/TR 14049:2000 (ISO 2000) (open loop recycling)			−11.5 %	−26.1 %	−27.5 %	−25.6 %	−22.1 %	System approach according ISO/TR 14049:2000 (ISO 2000
20	Sold steam products from incineration in MSWI	0 %	100 %	−26.4 %	−4.2 %	−2.1 %	−5.6 %	−29.3 %	Steam from waste incinerators is not saleable in some regions
Plastic crates end of life									
21	Share of plastic to secondary granulate	100 %	50 %	24.0 %	0.1 %	2.9 %	22.4 %	21.0 %	50 % incineration of polymer crates considered
22	Value of secondary granulate in relation to primary	70 %	100 %	−7.5 %	−3.8 %	−3.2 %	−20.5 %	−19.3 %	100 % value means that the secondary granulate would be used in vegetable crates again
23	Sold steam products from incineration in MSWI	0 %	100 %	−1.1 %	−0.3 %	−0.2 %	−0.2 %	−1.2 %	Steam from waste incinerators is not saleable in some regions

influencing the production of plastic crates results in only minor changes to their environmental profile.

Service life Re-usable systems are mainly characterized by the number of fillings per crate within their service life. As the plastic crates can be used multiple times, the average lifetime and the number of fillings during the lifetime have to be considered. Primary data give 4.8 fillings per year and an average life time of up to 20 years (Albrecht et al. 2009); thus, in the conservative baseline scenario, a 10-year lifetime per plastic crate is assumed, resulting in 50 fillings per crate. The parameter nos. 13 and 14 take into account the influence of the plastic crates' lifetime within the re-usable system, which affects the total number of fillings per crate. Parameter no.13 considers an average lifetime of 6 years per crate, showing the influence of a fairly short lifetime. Parameter no. 14 assumes a 20-year lifetime of the re-usable crates, as a close-to-reality scenario. The number of fillings per crate within its lifetime has a main influence on the performance of a re-usable system. Compared to the single-use wooden boxes, 40 to 60 fillings, depending on the respective impact category, need to be reached within a re-usable crate's lifetime to be environmentally preferable. This is in average reflected by the considered baseline scenario. Compared to the single-use cardboard boxes, the breakeven is reached already between 5 and 15 fillings, which represent lifetimes between 1 and 3 years. As a re-usable system is intended to run as long as possible, this is seen just as a theoretical number, as reality is somewhere between 10 and 20 years lifetime with about 5 to 10 fillings per year, resulting in a realistic number of fillings between 50 and 200 fillings per crate during its lifetime. An increase in the number of fillings per crate in the re-usable system results in an improved environmental performance over the whole packaging system related to the functional unit. Thus, the re-usable option shows always environmental advantages under an intended use of the multi-way system.

With an increasing number of fillings accompanied with an increasing number of trips made by the re-usable packaging in its lifetime, proportion of service-life emissions gains in importance within the re-usable system in comparison to the decreasing proportion of production and the end-of-life phase. Compared to the single-use systems the overall environmental impacts per functional unit decrease as per filling the service-life emissions are lower than the single-use box impacts. However, the additional advantage in environmental impacts caused by an increasing number of fillings per crate aspired slows down with a rising number of loops.

Although the variation of transportation distances is not a dedicated object of investigation and an average European transport distance could be calculated, some qualitative conclusions can be drawn. The backhaul trips for the re-usable system become more significant when significantly longer transport distances are considered. This means, fruit and vegetable transportation over significant longer transport distances tend to favor single-use packaging as the backhaul is not necessary. This is, for example, also true for overseas transports. The transportation over shorter distances tends to favor re-usable packaging, as the service-life system and the connection to the washing centers are optimal.

End of life In contrast to the production and service life, where the number of parameters is relatively well determined, the consideration of the end-of-life phase offers a wide range of values within the given scenarios.

Regarding the wooden boxes, two potential end-of-life treatment options are considered. The first option is the recovery of the embodied energy through incineration and the production of electricity. The second option is the material recycling of wood waste as raw material into the particleboard industry (no. 15 and 16). This second option is mainly relevant in Southern Europe, and therefore, only the additional fuel consumption of transports to Southern Europe caused by the weight of the wood is included, to make the figures independent from a transport demand discussion.

The recycling of cardboard includes the impacts from material recycling and the energetic recovery of the embodied energy. The variation of parameter no. 19 assumes a higher share of cardboard returning to the pulp and paper industry as a secondary resource. Within the representative baseline scenario, only 17.6 % of secondary material is returned (FEFCO 2006), as a higher share of primary fibers is needed to ensure a sufficient level of paper quality for the fruit and vegetables boxes. On average, within the European cardboard sector, around 55 % of cardboard is recycled into secondary material (FEFCO 2006). Parameter no. 19 corresponds to this higher cardboard recycling rate. A corresponding approach is developed in ISO/TR 14049 (ISO 2000). There, open loop recycling is considered, meaning that the material is not necessarily recycled into the same material or application. In this approach, allocation factors for the emissions released in the different steps were calculated based on the recycling rates and times of reuse. Applying this approach here does not change the overall findings of the study, although the results for the cardboard boxes improve between 11 % for GWP and 28 % for EP.

The amount of broken plastic crates proceeding to re-granulation is considered to be 100 % in the baseline scenario, but with a potential quality loss resulting in a residual value of 70 % compared to primary plastics. According to the data collected, this is the case for the investigated plastic crate system. Nevertheless, it is of interest to see the influence of a changing end-of-life option for plastic crates (no. 21 and 22). The overall results show up to 24 % higher impacts for plastic crates in ozone depletion, summer smog, and global warming, if 50 % of the crates go to incineration and only 50 % are re-granulated.

For all three transport packaging systems, parts of the waste flows are fed to the recovery of embodied energy in MSWI plants (no. 17, 20, 23). The use of the steam produced in these plants is viable and state of the art in several countries in the EU. However, in the European average, it plays a minor role, due to the unavailability of steam consumers or steam grids at the solid waste incineration plants. Steam recovery and sale was therefore not considered in the baseline scenario. The influence of the option to sell the steam as a valuable product is assessed as a parameter variation. In the case where the steam can be used and therefore sold, the life cycle impacts for all three systems decrease. The environmental impacts of the wooden boxes decrease most significantly, followed by cardboard and plastics. For the wooden boxes, a large decrease of the global warming potential occurs, because the incinerator emissions are counteracted by the production of both electricity and steam.

In summary, the environmental comparison shows that the differences in the three transport packaging systems analyzed reflect the system characteristics; two are single-use systems and one is a re-usable system. The two single-use systems are both based on the renewable feedstock wood and wood fibers whilst the re-usable system is fossil based. The life cycle performance of the single-use systems is mainly characterized by the choice of feedstock and the related manufacturing processes as well as the end-of-life option taken. Wooden boxes are easy to produce and show a good life cycle performance although they are not comparable to the high-tech cardboard and plastic products which exhibit more homogeneous material characteristics.

The high-quality requirements of transport packaging lead to high material requirements, in the case of cardboard to the necessity of Kraftliner and Semi-Chemical Fluting as main materials. The production of cardboard is therefore very intensive in terms of energy and chemical use. Although the cardboard industry has a high recycling rate, the considered high-quality boxes consist of more than 80 % primary material. The benefits at the end of life therefore do not completely counteract the impacts of the production phase. For both single-use systems, the service life plays a minor role in the life cycle.

The main environmental impacts for the re-usable system arise from the service life. There are two reasons for this: Firstly, the plastic crates have twice the weight compared to the other boxes and therefore resulted in higher fuel consumption and related emissions in transports. Secondly, the washing process requires additional energy and causes wastewater emissions. The material recycling at the end-of-life phase results in environmental credits from the recovery of secondary granulate to be used again in a similar application. With an increasing number of fillings, the re-usable system becomes more favorable compared to the single-use systems. This is because the energy demand and emissions of the washing process and the related logistics of the re-usable systems increase at a slower rate than the decrease in energy demand and emissions of plastic crate production through a lower need for plastic crate production.

Overall, plastic crates and wooden boxes have a lower impact in the chosen impact categories in comparison to cardboard boxes, for fruit and vegetable transport in Europe. The plastic crates system has the most favorable environmental impact compared to the other systems. For GWP and ADP, the results are similar for the wood and the plastic systems. The high impacts for the cardboard boxes are mainly due to the need for high-quality cardboard and therefore an intensive production process. The cardboard boxes may be further optimized from a design and shape which could lead to less material demand for the same capacity.

3.3 Economic evaluation of the transport packaging systems

Figure 4 below shows the results of the life cycle costing analysis of the three fruit and vegetable transport packaging systems. The analysis shows that the re-usable system is the most cost effective over its life cycle. Strictly speaking, these prices do not only include costs, but also revenue for the packaging producer. However, as this price occurs as a cost for the customers, it is considered as such. The transport of the new boxes/crates to the growers incurs transport costs. For the plastic crates, additional costs for the washing, sorting, and crate replacement after they have been used are considered. Transports during the service life take into account the cost for transporting empty boxes back to the growers and other transport costs related to the logistical tasks of a re-usable transport packaging pool provider. *Edge protection* is the cost for the protection of cardboard edge of the full pallets if they are loaded with wooden or cardboard boxes to enhance stability and protection of the freight. The *Bonner Notiz* is a charge for non-reusable transport packaging, which is 0.6 % of the value of the transported goods. The end of life cost denotes the cost for removing the wood waste in the case of the wooden boxes, while the revenue end of life denotes the revenue for cardboard waste and used plastic crates. The transportation cost of the full crates from producer countries (growing areas) to consumer countries is not considered in the cost analysis. The only difference between the crate systems originates from the different weight of the boxes/crates. This could lead to additional diesel consumption by the trucks loaded with plastic crates in comparison to trucks loaded with wooden or cardboard boxes; however, the effect is estimated to be of minor relevance.

The LCC covers all necessary costs to run the respective transport packaging service system according the functional unit. This includes the most important steps in the value chain. Neglected aspects are negotiable matters of expense like the costs for the fruit and vegetable transportation itself and revenues from the rental of boxes and crates. The dominating cost

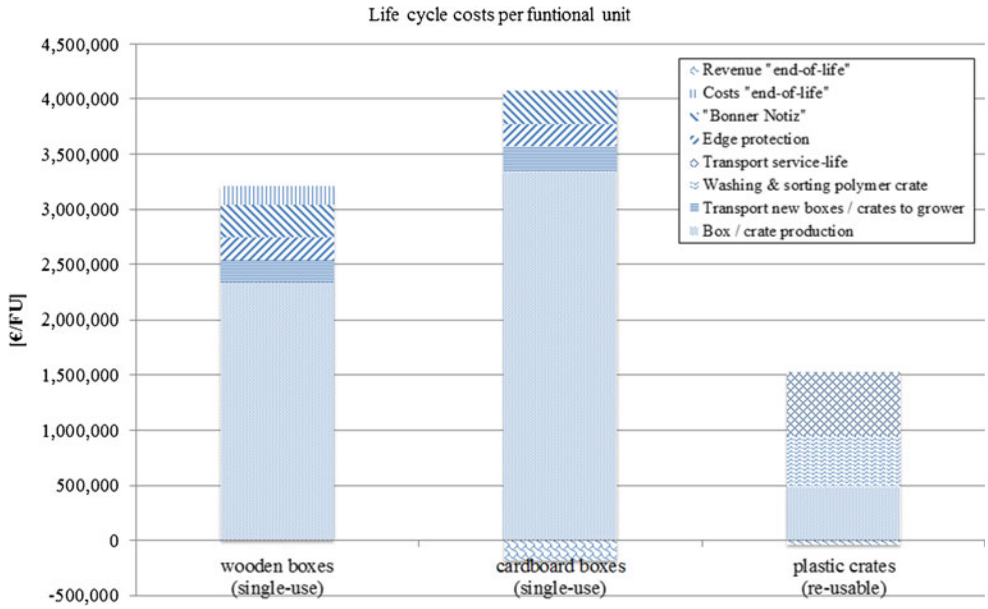

Fig. 4 Life cycle costs of the three systems over the entire life cycle (production of boxes/crates, transportation, washing (where present), and end of life)

drivers for both single-use systems are the boxes themselves, while for the re-usable system, the additional costs are also relevant. Overall, the service of one functional unit of the re-usable plastic crate system costs around half that of the single-use systems. The cost data are mainly derived from industry (Euro Pool System 2008, IFCO Systems 2008) and market experts (Fraunhofer IML 2008).

3.4 Social indicators

The social effects show a differentiated picture for the different indicators. As mentioned in Section 2.4, the applied indicators are at an inventory level. The production phase of the cardboard boxes shows the highest working time (150 s/box), followed by the plastic crates (120 s/box) and wooden boxes (85 s/box) related to the entire value chain. This is mainly caused by the highly processed and work-intensive upstream products. The working time's share of women employment is highest for plastic crates with approx. 28 %, followed by wooden boxes with approx. 18 % and cardboard boxes with approx. 5 %. This is mainly driven by the high share of employment in the wooden and cardboard box systems that is in forestry and logging, which is male dominated due to its physical labor. Within the chemical and plastics industry, the share of female work is higher.

When considering production and operation, all three systems require a relatively large share of low-qualified employees. The description of qualification levels addresses the qualification required for a job position rather than the actual qualification of the employees; it ranges from level A (master degree and above) to level E (untrained or short-term trained workers). For the re-usable system, the low-qualified ones are mostly employed for washing and sorting; for wooden boxes and cardboard boxes, they are employed for the production step, mainly in forestry and logging. As a long-term result, low-qualification jobs are ensured.

In comparison to the single-use box systems, the re-usable plastic crate system shows a very low lethal accident rate (Fig. 5). For the wooden boxes, the high lethal accident rate results from the logging of wood.

A considerable achievement is obtained using the LCWE method, in that the social indicators can be quantified along the life cycle of a product. This approach is based on the same product life cycle model as LCA; as background, it uses statistical data concerning social issues which are available for most of the highly developed countries. LCWE data sets are integrated in the GaBi software and database with a respective documentation of the employed data sources (GaBi 2008b). LCWE data is gathered on the level of industry branches and broken down onto the level of production processes. Hence, mean LCWE profiles are dedicated to the specific production processes, which is desired to minor the influence of spikes. The dedication of mean LCWE profiles is important to not overstate indicators which describe events with a very low probability of occurrence, like accidents. The statistical significance increases through the extension of the control sample. This leads to an increase of the underlying reference on the one hand and therefore to a *de-specification* of the determined LCWE profile on the other hand. *Process specificity* and *statistical significance* act antagonistically. This correlation and the possible deduction of a rule to apply a sufficient aggregation level of particular data collections is an important but pending question for (some) social indicators. Challenges remain regarding the interpretation of the results for some indicators; for example: is a high working time to be assessed as a positive or negative impact? Furthermore, the development of additional social indicators to be used within the LCWE method would clearly increase its significance.

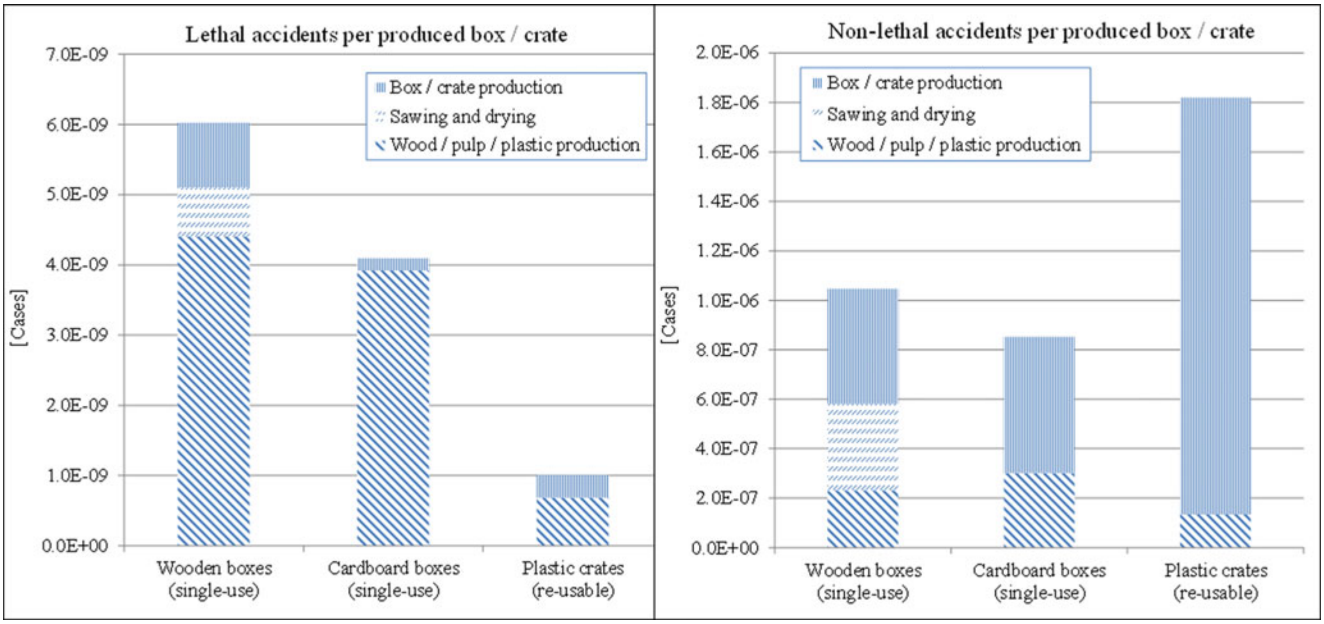

Fig. 5 Lethal and non-lethal accidents per produced package

4 Sustainability consequences of the influence of the packaging on the product

In this study, the environmental impacts of fruit and vegetable transport systems are analyzed in different technical situations and with different boundary conditions. The environmental impact results are complemented with life cycle cost and life cycle working environment results, in order to obtain a more encompassing sustainability assessment. However, it must be acknowledged that in specific boundary conditions, some packaging systems show additional and/or intangible benefits such as: flexibility of design (shapes, appearance, printings, labeling); free choice of supplier; suitability for bar codes or RFID tags and other logistic systems; low weight, ease of handling and stacking; hygiene, occupational health and safety aspects; and prevention of food losses. These properties play an important role in the decision-making process of a packaging system and should not be neglected.

Recent LCA studies of food items and their packaging (e.g., Büsser and Jungbluth 2009; Silvenius et al. 2011) indicate that the transport of goods and their primary packaging cause only a minor share of the total environmental impacts of the studied system. However, in the specific case of fruits and vegetables, the study by Cellura et al. (2012) indicates that a more relevant share of total environmental impacts is caused by packaging and transport. Nevertheless, from an environmental perspective, the package's role to protect the product and distribute it undamaged to the final consumer must be considered when comparing different packaging solutions, especially for easily deteriorating fresh products with short shelf life, such as fruits and vegetables. According to Buzby et al. (2009), a significant share of the food losses (up to more than 50 %) in the USA take place between the producer and the retailer, which underlines the important role of transport packaging to prevent fruits and vegetables from spoiling and other losses. Different packaging-related aspects contribute to the prevention of losses that occur during transport of fruits and vegetables. For example, the fruits and vegetables might have been packed only in transport packages, as was the assumption in this study. However, in some cases, primary packaging, such as dividers and trays, can be used to further protect the products. Different packaging material properties may give preference to some materials over others in terms of protecting the fruit and vegetables. These properties include respiratory and barrier properties, the ability to maintain optimal humidity conditions, and the adaptability of the packaging to any specific treatment the product may require (Chonhenchob and Singh 2003; Remón et al. 2003; López Camelo 2004). In addition, it has been stated that the placement of the products in the transport package, whether packed in single or multiple layers or in horizontal or vertical placement, may impact the condition of some fruits and vegetables (Chonhenchob and Singh 2003, 2005). Furthermore, the conditions during transport and storage may be optimized through packaging. Different packaging materials have different responsiveness to the vibration caused by transportation (Chonhenchob and Singh 2003). Correspondingly, packaging materials have different heat transfer characteristics, which affect the ability of the package to adjust to the optimal storage temperature for the specific fruit or vegetable in question (Singh 1992).

According to Aworh (2010), plastic crates perform well in prevention of food losses because the crates are strong,

impermeable to moisture, possible to clean and sanitize, and have smooth surfaces and good stack stability. The smooth surfaces, which reduce the damages in the skins of fruits and vegetables, have also assisted the shift from wooden boxes to cardboard boxes and plastic crates (Aworh 2010). On the other hand, some vegetables such as radish and green onions have been found to stay fresh longer in wooden boxes because of the more suitable humidity conditions.

5 Conclusions and recommendations

The environmental results show that the re-usable plastic crates and single-use wooden boxes display almost similar results in GWP, AP, and POCP. For the other impact categories considered (EP, ADP), the re-usable plastic crates show the lowest impacts whereas the single-use cardboard boxes have the highest ones. These results are in accordance with the results of the study by ADEME (2000).

The further optimization potential for each transport packaging option could be identified. For single-use wooden boxes, system optimization of the environmental profile could be gained due to:

- The reduction of wood transports, especially long-distance transports of wood imports.
- The reduction of weight of wooden boxes (weight varies partly almost factor two for same capacity depending on design and the moisture of the wood).
- The kind of used wood. As poplar seems to be less intensive in forestry and box production, the broader use of poplar seems to be favorable.
- The energy recovery in end of life. Due to the fact that wooden boxes are not recycled into particleboard in central Europe, certain transport distances to southern European sites apply. Energy recovery of wooden boxes in central Europe therefore seems to be the most appropriate end-of-life option.

For single-use cardboard boxes, system optimization of the environmental profile could be gained due to:

- The box dimensions and, therefore, the amount of required material is a possible aspect of further optimization as this appears to have a relevant influence on the environmental impacts.
- The composition of papers concerning the primary and secondary fiber content playing a relevant role. Relatively less secondary fiber is used in the production of fruit and vegetable cardboard boxes with the required quality. If the share of secondary fiber could be increased, environmental impacts could be reduced.
- Energy recovery at end of life: Due to the fact that fruit and vegetable cardboard boxes are not recycled into fruit and vegetable cardboard boxes again, different options for end-of-life apply. The energy recovery of cardboard boxes seems to be an appropriate end-of-life option as electricity and steam products are resulting.

For re-usable plastic crates, system optimization of the environmental profile could be gained due to:

- An increasing number of filling per lifetime. Thereby the overall results are optimized as the most important life cycle phase is the use phase. If the lifetime is reduced, the use phase becomes relatively more important. Therefore a conservative number of fillings were chosen as baseline scenario.
- The increase of amount of secondary granulates in the production of the crates.
- The application of recycling. If closed loop recycling is not possible open loop recycling into high value applications should be applied. In this case most of the secondary granulates is used in crate production for other applications, reflecting about 70% of the primary granulates value in fruit and vegetable crate production.
- The improved washing and cleaning process being of relevance within the life cycle of re-usable crates. Therefore, any effective reduction in energy consumption and related emissions, emissions from washing water as well as improvement of efficiencies lead to an overall optimization, especially with respect to a high number of fillings per lifetime.

Regarding economic aspects, the re-usable system also shows advantages over the single-use systems. The highest share of the life cycle costs for wooden boxes and cardboard boxes occurs in the production phase, while for plastic crates, the service life is the main cost driver. The re-usable crates show a decrease in life cycle costs when increasing the number of fillings. The number of circulations per re-usable crate should therefore be as high as possible.

When assessing social impacts, plastic crates are the most preferable option in terms of the number of lethal accidents, and wooden boxes the worst. LCWE results should always be interpreted in the context of the societal boundaries and conditions, as the direction of the indicator scales is not as clear as in LCIA (e.g., not every context is a high share of highly qualified workers more preferable than a high share of lowly qualified workers). In this respect, a higher share of jobs by women and their qualification profiles might be assessed differently by the different interested parties: employers, employees of different qualification levels, and politicians. For example, female workers and politicians might welcome and therefore assess positively a high share of women workers, whereas employers may not due to a

potential higher share of part-time work for example. Nevertheless, it is highly recommendable to further explore and discuss this social assessment method, possibly by obtaining different user profiles with a predefined view on the indicators.

The current and ongoing discussion about sustainability highlights the necessity of assessment and quantification of a range of sustainability indicators. This study shows that a comparative sustainability assessment is feasible in a structured methodological way under similar boundary conditions and from a life cycle perspective. It is clear that such a study will not be able to cover sustainability exhaustively, but it can be concluded that certain sustainability aspects can complement an environmental life cycle assessment and provide important additional information for decision makers in policy and industry. Within this study, the underlying foreground life cycle inventory model was used as basis for the life cycle impact assessment as well as for the evaluation of economic and social aspects. Supplemented by the use of consistent background data, the study benefits from conformed system boundaries and a clear reproducibility and therefore can be easily updated in the future. An increased inclusion of the LCA aspects of food losses and the resulting benefits for the environmental performance of the respective transport packaging systems are envisaged as necessary research future activities.

A comparative sustainability assessment of fruit and vegetable transport packaging options will always be partial, as the packaging influences the amount and quality of the fresh food arriving to the consumer which consequently influences the total impact of the packaging–product system. However, life cycle decision making occurs based on both quantitative science-based information and built-in social and emotional rules (Fullana-i-Palmer et al. 2011). Therefore, further research is needed to help the decision-making process from a life cycle management perspective both in relation to the influence of packaging in the product life cycle and in relation to how the results are processed together with other societal and emotional factors.

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